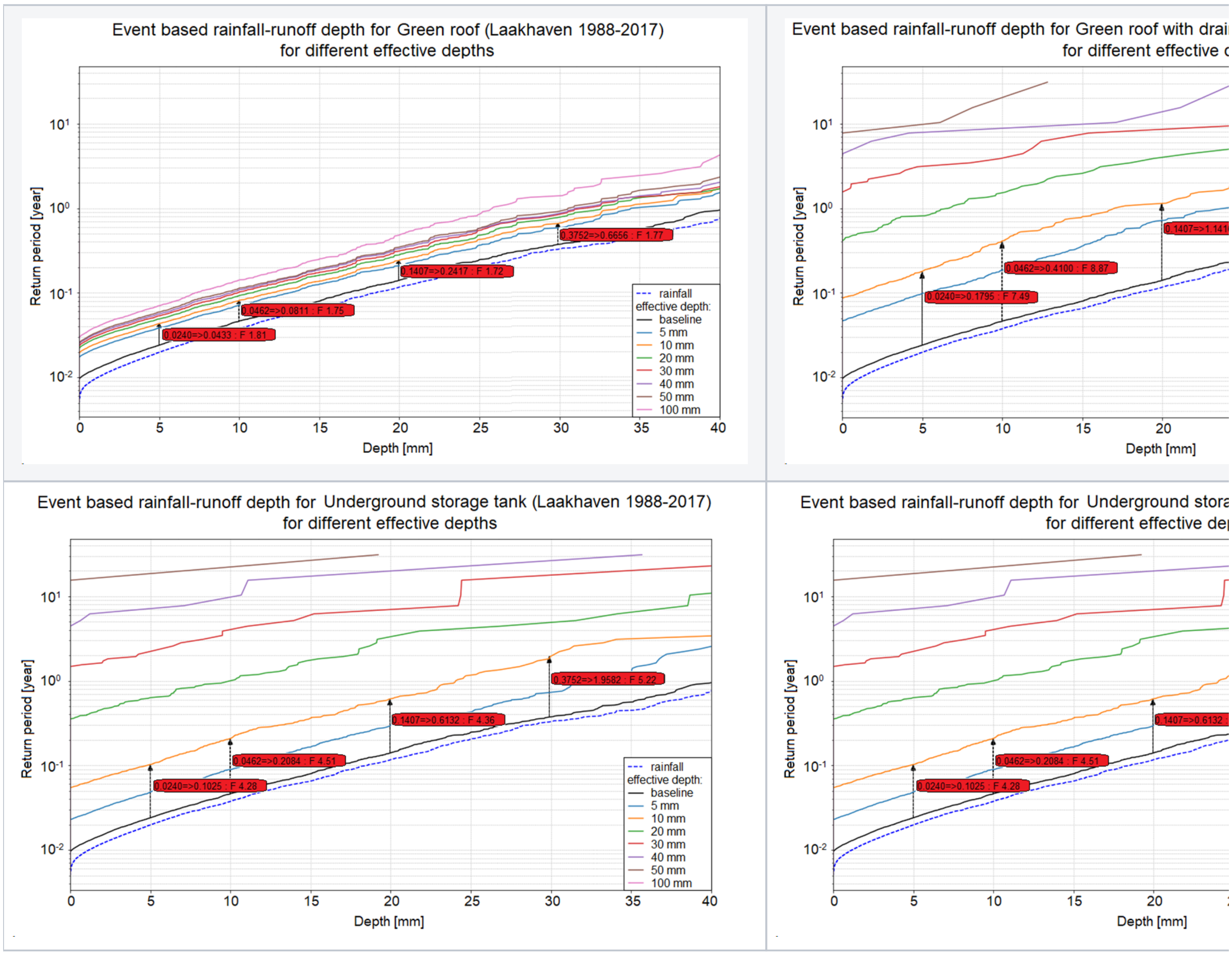
Calculation of runoff-factor

Factor for measures on runoff return period

Applying measures to reduce urban runoff results in an increase of the return periods of the runoff volumes. For instance, a runoff that currently is exceeded once every two years can be changed by applying a measure into a runoff that is exceeded once every three years. That implies that the damage that is caused by such a runoff will roughly occur 50% less frequently.

Calculation results of the urban water balance model indicate that measures change the return periods of runoff volumes by a constant factor. Figure 1 shows the calculation results of several measures applied in an area in Laakhaven (The Hague, The Netherlands). Continuing the example above, where a runoff return period of 2 years is changed into a runoff period of 3 years after applying a measure, the same measure will change a runoff with a return period of 20 years into a runoff with a return period of 30 years and a return period of 0.2 years will change into a return period of 0.3 years. The latter is very interesting, because that means that the effectivity of measures can be tested (in practice) during short periods of time.



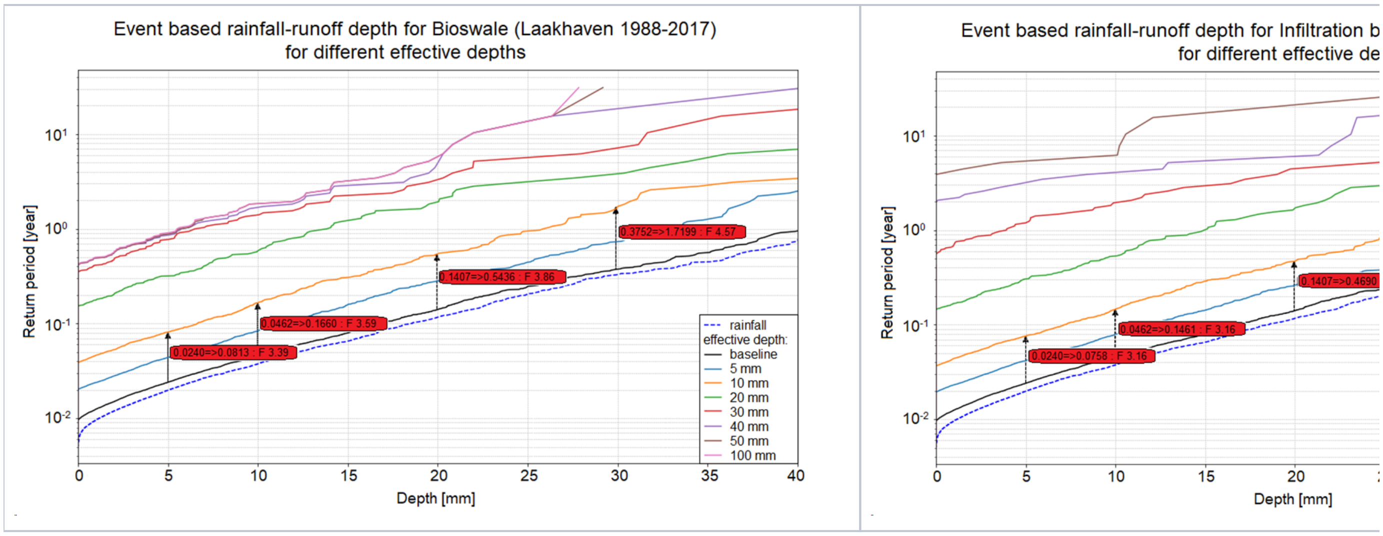


Figure 1 Simulation results of the effect of applied measures on the return periods of urban runoff volumes for Laakhaven over a 30-year period with an hourly calculation time step

Please note that the lines in Figure 1 are based on observed rainstorms over a period of 30 years. The number of rainstorms in this period is almost 6000, where a rainstorm means that at least some rain was recorded. The higher the total volume of a rainstorm is, the less frequent it is exceeded. Hence, the lines in the figure are much more fluent for low return times (left parts of all figures) than for high return times (right parts of the all figures).

Also, please note that the measures consist of a storage volume from where runoff is controlled. This can be runoff via groundwater (infiltration) or slow / delayed release to the drainage system. Basically, only evaporation from the measure itself reduces the runoff volume. In the method described above the controlled runoff is considered to be no part of the runoff volume of the measure, because we assume it will cause no problem in the drainage system. We are aware of the fact that this might result in an overestimation of the effectivity of the measure. However, we are convinced that this overestimation is relatively small. When the storage volume of the measure is exceeded, uncontrolled runoff occurs. This uncontrolled runoff is the measure runoff that is described above.

Measure factor determination

The effect of runoff adaptation measures is applied in the Climate Resilient City Tool (CRCTool), a map table tool to support urban planners by indicating the effectivity of climate adaptation measures that can be applied in urban project areas.

Separation of storm events

Small rainfall events result in filling the interception storage. Rainfall exceeding the interception storage capacity results in runoff (via SWDS) to open water. Runoff to open water results in discharge from open water to outside the model area. Runoff exceeding the defined discharge capacity of the model area results in storage in the open water part of the model area, where storage in the UWM is defined as a rise of the open water level above the defined target water level.

For determination of the SDF curves of the model area and for determination of the effects of adaptation measures we have to identify separate storm events. To this end we apply fixed periods between storage events and rainfall events. And we prefer using hourly data or even shorter intervals because of the rapid runoff characteristics of urbanized areas. By definition in the UWM, rainfall events are separated by 6 hours without rainfall and storage events are separated by a single time step without increased open water storage.

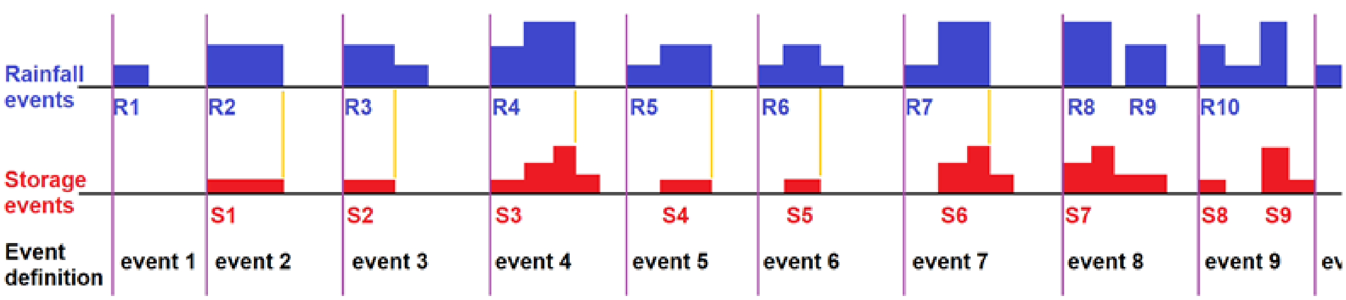


Figure 2 Examples of generation of storm events, based on rainfall events (blue) and storage events (red). Each storm event lies between two consecutive event separators (purple vertical lines).

Basically a new storm event starts at the first time step with rainfall after both previous rainfall and storage events are ended. This also goes in case a storage event ends the time step prior to the start of a new rainfall event (i.e. no storage at the first time step of the new rainfall event, like S9 in figure 2). Multiple rainfall events can result in a single storage event (R8 and R9 in figure 2). In case a single rainfall event results in multiple storage events, these storage events are combined to a single storm event (S8 and S9 in figure 2). Event separation lies at the start of each new storm event.

For each defined storm event the following parameters are determined:

- Total rainfall (rain depth)
- Maximum rainfall during a single time step of the event (peak rainfall intensity)
- Total runoff (runoff depth)
- Maximum runoff during a single time step of the event (peak runoff intensity)
- Maximum storage during a single time step of the event (peak storage)
- Total evapotranspiration
- Total groundwater recharge

The event definition is applied in the baseline run, in which the available time series of rainfall and evaporation are applied on the current drainage situation, without any adaptation measures applied. In the baseline run the area discharge capacity is to be set by the model user. In case the area discharge capacity is unknown, a default capacity of 3 to 4 times the average daily rainfall is advised. For calculation of the effect of measures the same event separation is applied as in the baseline run.

Note 1: In case the selected model time step is larger than 6 hours (for instance 1 day), rainfall events are separated by a single time step without rainfall.
Note 2: The area discharge capacity can either be user defined, or a default value can be applied. This default value depends strongly on the climate conditions of the modeled area. A practical value for a default discharge capacity for the base run for event separation is 3 to 4 times the average daily rainfall. In case the actual discharge capacity of the area deviates much from this practical value, it is strongly advised to apply this practical value instead.

<u>Determination of runoff factor</u>

Steps to determine runoff factors for adaptation measures are:

1. Separate events (is automatically done after the baseline run):
   a. Separate rainfall events by six consecutive hours with no precipitation (Figure 2). Each rainfall event ends when the next rainfall event starts.
   b. Separate storage events by a single time step with no storage in open water (Figure 2). Each storage event ends when the next storage event starts.
   c. Separate combined storage and rainfall events.
   d. The same intervals are applied for the periods of the runoff events.
2. Calculate event-based rainfall depth, event-based baseline runoff depth (baseline is current situation) and event-based uncontrolled runoff depth (for situations with applied measure), where uncontrolled applies to measure overflow and normal runoff for the areas without measure.
3. Assign ranks to the data after arranging them in descending order of magnitude, calculate the probability of exceedance of each rank number with the Weibull formula (P=m/(N+1); where m is the rank assigned and N is the number of years) and calculate the corresponding return period T (T=1/P).
4. Plot the runoff depth against the corresponding return period for all results in a semi-logarithmic graph, and interpolate the points (see examples in Figure 1).
5. Repeat step 2 till 4 for various retention sizes of the measure.
6. As shown in Figure 1 we observe a linear shift of the line on a logarithmic axis, especially within the lower to medium range of return periods, implying a measure with a certain retention depth reduces the recurrence frequency of certain runoff depth and increases the return period by a constant factor.
7. In order to make a reliable estimate of the shift (= the factor), the model calculates the average of the factors of the changes of return periods for a pre-defined set of runoff depths (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 40, 50 mm). Runoff depths that not occur (in some measures) are automatically excluded from the average.
8. The derived factor is only valid for the measure’s inflow area. Multiplying the return period of the normative runoff of the baseline situation (for which the drainage system is designed) by the factor will result in the new return period of the normative runoff. This, however is only valid for the runoff period from the measure inflow area.
9. The return period of the normative runoff from the entire project area is derived in the CRCTool. How this is done, is explained below in a separate section.

In the Netherlands the normative runoff for urban areas has been defined based on a cost benefit analysis. This has been done several decades ago, resulting in a return time of normative runoff of 2 year. Therefore, we define normative runoff as the runoff event with T=2year runoff depth. From above we know that applying adaptation measures will increase the return time of the normative runoff by a factor. This is how the runoff factor for frequency reduction is defined.

Please note that the runoff frequency reduction factor is not obtained from scientific derivation, but an interesting finding from the empirical graphic method.

From measure inflow area to project area

Normally an adaptation measure in urban areas will be applied to adapt runoff from paved areas. For the translation of the factor of the measure inflow area to the project area we assume that the inflow area of runoff water to the measure totally consists of paved area (Figure 3).

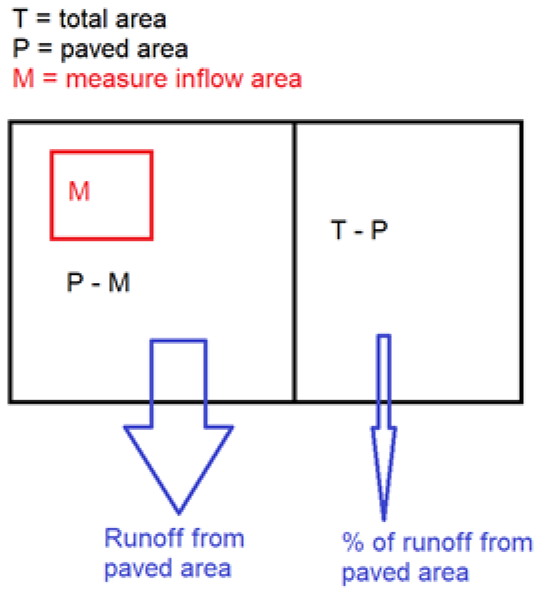


Figure 3 Definition of areas

Part of the project area T (total area) consists of paved area P. The rest of the area T – P consists of unpaved area and open water. Fast runoff in urban areas is the runoff that can cause flooding. Most of the fast runoff will come from paved areas. Unpaved areas will mainly generate slow runoff (via infiltration and groundwater flow) and only generate fast runoff when both the infiltration capacity of the soil and the storage capacity on the soil surface are exceeded and/or when the soil is completely saturated. Open water, as defined in the urban water balance model, only has fast runoff, which is basically direct rainfall.

The fast runoff from the non-paved areas can be estimated as a percentage of the fast runoff from paved area. This percentage will depend mainly on the area relative to the total area and on the soil composition. However, in general the order of magnitude can be estimated at 5% of the fast runoff from paved areas.

Based on these assumptions we can translate the runoff return period factor for the measure inflow area to a factor for the entire project area by applying the following formula:

$$F_{tot} = \frac{A_p \cdot e^{\left(\frac{A_{mi} \cdot \ln(F_{meas})}{A_p}\right)} + \frac{Perc_{RA}}{100} \cdot (A_{tot} - A_p)}{A_p + \frac{Perc_{RA}}{100} \cdot (A_{tot} - A_p)}$$

with:

F_{tot}	Factor for total area
F_{meas}	Factor for measure inflow area
A_{tot}	Total area
A_p	Paved area
A_{mi}	Measure inflow area
$Perc_{RA}$	Runoff from the rest of the area, estimated as a percentage from the runoff from paved area

Basic argumentation of this formula is that the runoff return period in years is an exponential function of the event runoff in mm (see examples in Figure 1). That implies that the runoff in mm is a Natural Logarithmic function of the return period in years

This formula differs from the applied formula in the first version of the CRCTool:

$$F_{tot} = \frac{A_{mi} \cdot F_{meas} + (A_{tot} - A_{mi}) \cdot 1}{A_{tot}}$$

This formula can lead to strange results. For instance, for a 100% paved area when the measure inflow area is only 1% of the total area and the factor for the measure inflow area is 100 (i.e. solving almost all runoff problems) the factor for the total area would be 1.99, indicating that by reducing the runoff in 1% of the total area to zero, the return period of the normative runoff in the total area would change from 2 years into almost 4 years.

The new formula will result for the same measure into a factor for the total area of 1.048, leading to a return time for the normative runoff of 2.09 years. Since the calculated factors can exceed 100 by far, the differences can even be a lot larger.

In less extreme conditions, regarding measure inflow area and accompanying factor, the differences between the old and new formula are a lot smaller.

Combination of measures

If multiple measures are applied in a project area the resulting factor can be determined by multiplying the individual factors.